

Dynamic Changes of Plateau Wetlands in Madou County, the Yellow River Source Zone of China: 1990–2013

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Abstract Plateau wetland is a special kind of ecosystem highly vulnerable to change and shrinkage owing to natural fluctuations and external disturbance. In the past wetlands have been mapped as a single category, making it difficult to assess the relative importance of natural and anthropogenic variables in the change. In this study, wetlands in Maduo County in the headwater zone of the Yellow River were mapped into six types based on their hydro-geomorphic properties from Landsat satellite images of 1990, 2001 and 2013. The changes between wetlands and non-wetlands in two separate decades were detected from the produced wetland maps in ArcGIS. The obtained results indicate that there were 8542 km² of wetlands (about 33 % of the county's territory) in 1990. They shrank to 7,061 km² in 2001, but expanded to 7,972 km² in 2013. During 1990–2001 all six types of wetland suffered a loss, with alpine wetland shrunk the most, followed by piedmont wetland. In general, the higher the ground at which a wetland was located, the more it lost. This trend of decrease was reversed in almost the same order during 2001–2013. Namely, the higher the ground of the wetland, the more it gained. Analysis of climate data suggests that

temperature is not critical to the observed change in wetland area. Instead, it is the warm season rainfall that has exerted the most influence over the observed change. Population bears no clear relationship with wetland change. The reduced sheep population by 54.5 % during 2001–2013 helped to improve the eco-environment of the study area and to reverse the shrinking trend of wetlands.

Keywords Wetland change detection · Causes of wetland change · Remote sensing · Causes of wetland loss · Maduo · The Yellow River source zone of China

Introduction

As an ecosystem able to provide the most valuable ecosystem services per unit area, wetlands play an indispensable role in maintaining a healthy environment. Apart from being an important habitat for aquatic plants and wildlife, including *Grus nigricollis* (Song et al. 2014), plateau wetlands enjoy one of the highest biodiversities per unit area for any ecosystem. However, located at a high elevation, they are extremely vulnerable to shrinkage and degradation due to environmental change and external disturbance. Consequently, a huge amount of research has been carried out to study wetlands, including their ecological fragility, unique hydrological characteristics, soil properties, and plant diversity (Valiela and Fox 2008; Cao and Fox 2009). So far researchers have examined changes in wetland plants and degradation of the wetland ecosystem (Bolca et al. 2007; Rebelo et al. 2009). Since the 1990s remote sensing has found increasing applications in wetland monitoring (Pantaleoni et al. 2009). The applications of remote sensing to wetland studies have been comprehensively and systematically reviewed by Ozesmi and Bauer (2002). Adam et al. (2010) overviewed the mapping of

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wetland vegetation, and estimation of some biochemical and biophysical parameters of wetland vegetation from remote sensing data. Johnston and Barson (1993) developed simple remote-sensing techniques suitable for mapping and monitoring inland wetlands from multi-temporal satellite imagery. After comparing Landsat TM, SPOT and aerial photographs in extracting tropical wetland information, Harvey and Hill (2001) found that TM imagery is able to achieve an accuracy comparable to that of SPOT. Salari et al. (2014) demonstrated the feasibility of using high resolution WorldView-2 satellite imagery in developing quantitatively ecological baseline data for wetlands.

Wetlands are commonly mapped from satellite imagery using visual interpretation and automatic methods such as object-oriented image classification and decision trees (Frohn et al. 2011; Gong et al. 2010; Dronova et al. 2011; Liu et al. 2014). Object-oriented segmentation of Landsat data, together with GIS techniques, enables identification of isolated wetlands >0.20 ha in size (Reif et al. 2009). After wetlands at different times are mapped, it was possible to detect their changes in a GIS (Zhang et al. 2009; Xue et al. 2015). Liu et al. (2014) quantitatively analyzed the spatial and temporal changes of wetlands in the Yellow River Delta, China after they were mapped from multi-temporal satellite data. Wang et al. (2007) analyzed the dynamic change characteristics of the typical frigid wetland on the Qinghai-Tibet Plateau over the last 40 years.

Automatic classification of wetlands is a highly challenging task due to the spatial co-existence of water with aquatic plants and constrained site accessibility. Thus, classification is restricted to broad types. For instance, Kindscher et al. (1997) identified and mapped six spectrally and ecologically distinct montane meadow community types within the Grand Teton National Park based on mean wetland values and plant species cover. Zhang et al. (2011) classified wetlands in China's Sanjiang Plain into water, marsh, and non-wetlands. Judd et al. (2007) mapped salt marsh vegetation into three types at an accuracy of 85.1 %. Lane et al. (2015) classified freshwater wetlands and aquatic habitats in the Selenga River Delta of Lake Baikal, Russia at an accuracy of 86.5 %. Midwood and Chow-Fraser (2010) differentiated six wetland habitat classes (emergent, high-density floating, low-density floating, meadow, water, and rock) from IKONOS satellite images using an automated, object-based, image-analysis approach with a mean accuracy of 87.4 %.

Although automatic classification of remotely sensed data is a rapid way to map wetlands, the low accuracy achievable means that a visual method has to be used (Navatha et al. 2011; Fickas et al. 2015), especially if wetlands are to be mapped into detailed types, such as lacustrine, riparian, riverine and emergent. Navatha et al. (2011) visually interpreted satellite images to map wetlands into rivers, reservoirs, seasonal lakes, perennial lakes, and ponds. So far

nobody has attempted to map wetland types from satellite imagery, incorporating hydro-geomorphic features. On the other hand, it is important to produce such a detailed wetland map and to detect changes among different types of wetlands as the results are conducive to revealing the cause of wetland degradation. Gao et al. (2013) classified all wetlands on the Qinghai-Tibet Plateau into seven types of alpine, piedmont, valley, floodplain, terrace, riverine and lacustrine based on their hydro-geomorphic features. In this study, wetlands in a singular region in the headwater zone of the Yellow River were mapped as these types by taking into consideration their position in the landscape, and to detect the change between different types. This innovative analysis should be of interest to be applied to wetlands in different parts of world as it is conducive to revealing the impact of environmental conditions on wetland change.

The purpose of this study is to contrast the dynamic changes among different types of wetlands in Maduo County on the Qinghai-Tibet Plateau from multi-temporal Landsat satellite imagery in two separate decades. The specific objectives are: (a) to explore changes between different wetlands in relation to their position in the landscape; (b) to compare the changing behavior of wetlands over two separate decades; and (c) to evaluate the importance of both natural and anthropogenic variables to the observed changes in wetland areas detected using a Geographic Information System (GIS). These objectives are achieved by mapping wetlands into different hydro-geomorphic types in ArcGIS, and by linking detected changes in wetlands to changes in both natural and anthropogenic variables over the corresponding study period.

Study Area

The area selected for this study is Maduo County situated in the northwestern Guoluo Tibetan Autonomous Prefecture of Qinghai Province, western China. Ranging from (33°50'N, 96°50'E) to (35°40'N, 99°20'E) in its geographic extent, it covers an area of 25,253 km². Maduo has a mean annual temperature of -4 °C and a mean annual precipitation of 305 mm, only a small portion of the annual evaporation of over 1200 mm. The county lies in the central Qinghai-Tibet Plateau with an average elevation of 4200 m above sea level (a.s.l.). Its frigid alpine climate allows only herbaceous plants and dwarf shrubs to survive in this harsh environment with two seasons of cold and warm (the warming season lasts three months from June to August). Owing to the abundant grassland resources that comprise 87.5 % of the county, animal husbandry is the predominant economic activity. Typical pasture includes alpine steppe grassland and alpine meadow, both being grazed chiefly by yaks and Tibetan sheep. Maduo County used to enjoy the highest per capita income in China in the early 1980s, but has become one of the poorest due to

severe grassland degradation. The county has a rich water resource, with many rivers and lakes with a combined area of 1674 km². Located within the source zone of the Yellow River, these lakes make a significant contribution to its channel flow. Distributed in this zone are diverse types of wetlands, the most common being swampy meadows found at a wide range of elevation. Owing to the lack of conscience in their protection, some wetlands have shown signs of shrinkage and degradation while others have been degraded even to the severe level (Li et al. 2014).

Methodology

Data Used

Landsat satellite images recorded in 1990, 2001 and 2013 were used in this study. They were downloaded from the Geographic Spatial Cloud Data clearinghouse (<http://www.gscloud.cn>) maintained by the Computer Network Information Center of the Chinese Academy of Sciences. Given that wetlands are full of lush vegetative cover that is the most distinctive during the warm growing season, only those images recorded during June–August of each year were deemed suitable and selected. This season also coincided with the field work undertaken during late July of 2012 and early August of 2013. All useable images had less than 10 % cloud cover. Due to the irregular shape of Maduo, three scenes of imagery were needed to cover the entire county. Preferably, all three should be recorded on the same day. However, contamination by clouds means that images recorded in other dates had to be used. They were 28 and 30 of August for the three 1990 Landsat 4–5 Thematic Mapper (TM) images. In 2001, the three acquisition dates of Landsat 7 Enhanced TM Plus (ETM+) images were 3 and 12 of July, and 13 of August. For 2013, the three Landsat 8 Operational Land Imager images were recorded on 21 July and 13 August (two images). Thus, there is a maximum temporal disparity of 40 days between scenes of the same year. This difference is considered insignificant given that wetlands do not change noticeably within such a short interval during which ephemeral flash floods may affect wetland area at the local scale, but this influence is not considered significant on the satellite imagery of 30 m by 30 m resolution. All the spectral bands of Landsat images were downloaded. These images have been projected to the Universal Transverse Mercator projection. These data are the standard level 1 products saved in the GeoTIFF format.

Data Processing

The collected Landsat TM/ETM+ images were geometrically processed in ENVI (version 5.0) in which the shared portion of overlapping images was clipped. Afterwards a mosaic was

produced from the clipped images of the same year. In ArcGIS the mosaic image was trimmed using the Maduo County boundary layer created out of the boundary map of Maduo County collected during the field work of 2012. A color composite of bands 7 (shortwave infrared), 4 (near infrared) and 2 (green) was displayed on screen for visual interpretation. These bands are considered the best in detecting vegetative cover while band 4 is highly sensitive to the presence of water. This composite allows the spectral difference between ordinary grassland and swampy meadow to be well distinguished. Since the images were visually interpreted, there was no need to normalize the multiple-date data to account for radiometric variations caused by solar illumination conditions, atmospheric scattering, atmospheric absorption and detector performance.

Extraction of Wetlands

Prior to image interpretation, extensive field work was carried out throughout Maduo in July 2012 and August 2013, during which visits were made to six types of wetlands so as to establish their image identity and to construct their interpretation keys. Only six types of wetlands were selected because it was difficult to locate terrace wetlands in the field. Their positions were also logged with a GPS unit, with which their location on the satellite images was determined. In total, 27 sites were collected, of which 6 sites were investigated in 2012 and 21 sites in 2013 (Table 1). According to the different classes, there were 3 alpine wetlands, 5 piedmont wetlands, 5 floodplain wetlands, 4 valley wetlands, 4 riverine wetlands, and 6 lacustrine wetlands. In addition to the broad type of wetlands, the overall landscape in which the wetland occurs was also noted. During image interpretation, attention was then paid to the image properties, including physical size, shape, texture, and location in the surrounding environment (e.g., on the mountain slope or at the mountain foot). Interpretation was undertaken in ArcGIS (version 10.0) in which the color composite of 2013 was displayed, a polygon shape file was created, and polygons representing different types of wetland were delineated on screen. During interpretation the color composite was frequently zoomed in to resolve more subtle color variations. Occasionally, fine resolution satellite imagery from Google Earth was consulted. The interpretation was based on the minimal resolving power of the satellite imagery, incorporating the “Wetland Classification Standards” set by the National Forestry Bureau (GB/T 24708-2009). At the end of the manual interpretation, a detailed wetland map was produced showing the distribution of all six types of wetland. The acquired wetland map was subsequently edited, with each type assigned a unique code to prepare for change detection. The same process of interpretation was repeated for the 2001 and 1990 composites. In the end three wetland maps of 1990, 2001, and 2013 were generated. Accuracy assessment was

Table 1 Area of wetlands by type and its change from 1990 to 2013 (unit: km²)

| Wetland type | 1990 | 2001 | 2013 | 1990–2001 | 2001–2013 | 1990–2013 |
|--------------|---------|---------|---------|-----------|-----------|-----------|
| Riverine | 201.42 | 175.81 | 190.51 | –25.61 | +14.7 | –10.5 |
| Lacustrine | 1750.8 | 1620.4 | 1780.35 | –130.4 | +159.95 | +29.55 |
| Alpine | 2798.96 | 2137.93 | 2447.32 | –661.03 | +309.39 | –351.64 |
| Floodplain | 1546.74 | 1341.72 | 1456.58 | –205.02 | +114.86 | –90.16 |
| Piedmont | 1458.69 | 1039.64 | 1238.54 | –419.05 | +198.9 | –220.15 |
| Valley | 785.36 | 745.63 | 858.78 | –39.73 | +113.15 | +73.42 |
| Total | 8541.97 | 7061.13 | 7972.08 | –1480.84 | +910.95 | –569.89 |

“+” means gain; “-” means decrease

carried out for the 2013 results since it was impossible to verify the accuracy of the 1990 and 2001 maps.

GIS Overlay Analysis

Two consecutive wetland maps (e.g. 1990 and 2001, 2001 and 2003) were overlaid with each other using the logic “OR” in ArcGIS to detect wetland changes. The derived overlay layer was explored to reveal the amount of change between wetlands and non-wetlands, as well as change between two possible wetland types in the table environment. The detected changes were summarized in a two-dimensional matrix. Apart from the absolute amount of change, a few change indicators, such as rate and percentage of changes, were also derived in MS Excel.

Change in Wetland Area It refers to the absolute amount of change in wetland area, and is calculated by subtracting the area of wetland in the ending year of a study period (S_2) from the wetland observed in the beginning year of the period (S_1), or

$$\Delta S = S_2 - S_1 \quad (1)$$

A positive ΔS signifies an increment in quantity while a negative ΔS suggests a decrease of change.

Velocity of Change (V) The rate of change (V) indicates the amount of change per annum. It refers to the speed at which wetland changes. It is calculated as

$$V = (S_2 - S_1)/T \quad (2)$$

In which T stands for the temporal interval between the start and the end years of the study period, expressed in years. Thus, V has the unit of km²·yr⁻¹.

Percentage of Change (P) It indicates the level of change between any two dates, expressed as the percentage of change in relation to the initial wetland area. Namely,

$$P = (S_2 - S_1)/S_1 \times 100\% \quad (3)$$

Results and Discussion

Wetland Abundance and Accuracy

In 1990, there were 8542 km² of wetlands in Maduo, accounting for 33.8 % of the entire county (Table 2). Of these wetlands, the largest is alpine at 2798.96 km², or nearly one third of all wetlands. Such a high prevalence is attributed to the dominance of tall mountains that experience frequent diurnal freezing and thawing in the warm season. Melting of snow and glaciers at extremely high elevations recharges downslope areas, forming extensive alpine wetlands. Also, the more abundant than usual rainfall at such a high elevation ensures that there is sufficient hydrologic recharge to the wetland system. The next most common wetland is lacustrine wetland at 1750.8 km² (20.5 %). Nicknamed the county of “thousands of lakes”, Maduo has many lakes, the most important being the Gyaring and Ngoring (Fig. 1). Both floodplain and piedmont wetlands have a similar size, accounting for 18.1 % and 17.1 % of the total, respectively. Piedmont wetland at the foot of mountains is frequently recharged by water flowing down-slope, melted snow or rainfall. Floodplain wetland is partially submerged during flooding, but fully exposed otherwise. As part of the river system, floodplain wetlands can be the former river bank after the channel has laterally shifted its course. In contrast, both valley and riverine wetlands are much smaller in area, accounting for less than 12 % in combination. Riverine wetland is associated chiefly with the Yellow River and its numerous tributaries. This minority status is caused by the limited area along river channels or at the bottom of valley floors between two mountain ranges.

Spatially, the distribution and physical appearance of wetlands in Maduo are governed by surface relief and morphology. Namely, both valley and riverine wetlands are narrow and linear in shape (Fig. 2a). In contrast, both lacustrine and alpine wetlands are rather extensive spatially due to the fact that lakes are huge and the mountain ranges widespread. Similarly, floodplain wetlands are also spatially extensive, and their location adjoins river channels, traversed by a channel in the middle, or to one side of the channel. This kind of spatial pattern of distribution hardly varied during the study period (Fig. 2b, c).

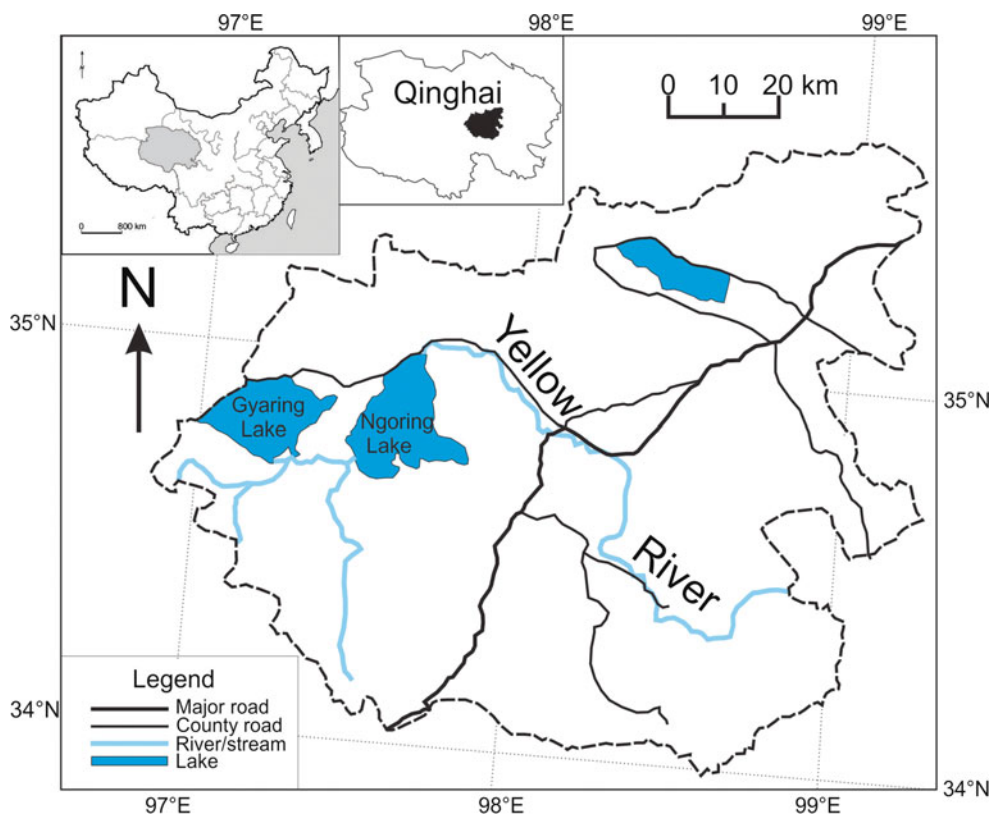
Table 2 Velocity ($\text{km}^2 \cdot \text{yr}^{-1}$) and rate (%) of change by wetland type from 1990 to 2013

| Wetland type | Velocity 1990–2001 | Rate 1990–2001 | Velocity 2001–2013 | Rate 2001–2013 | Velocity 1990–2013 | Rate 1990–2013 |
|--------------|--------------------|----------------|--------------------|----------------|--------------------|----------------|
| Riverine | -2.3 | -12.7 | 1.2 | 8.4 | -0.5 | -5.4 |
| Lacustrine | -11.9 | -7.4 | 13.3 | 9.9 | 1.3 | 1.7 |
| Alpine | -60.1 | -23.6 | 25.8 | 14.4 | -16.0 | -12.6 |
| Floodplain | -18.6 | -13.3 | 9.6 | 8.6 | -4.1 | -5.8 |
| Piedmont | -38.1 | -28.7 | 16.6 | 19.1 | -10.0 | -15.1 |
| Valley | -3.6 | -5.1 | 9.4 | 15.2 | 3.3 | 9.3 |
| Overall | -134.6 | -17.3 | 75.9 | 12.9 | -25.9 | -6.7 |

Accuracy assessment for the 2013 map in the field reveals that, of the 27 sites visited, A3 fell outside the Maduo County bound, and was excluded from accuracy assessment. Only one site (V2) was found to represent non-wetland, resulting in an overall accuracy of 96.2 %. This accuracy is highly comparable to the overall accuracy of 92.8 % achieved by Frohn et al. (2012) in mapping isolated wetlands (> 0.2 ha) at the sub-pixel level. If the confusion among different types of wetlands is taken into consideration, the accuracy is lowered to 80.8 %, which is deemed acceptable. The four mistakes among different types of wetlands are rivers wrongly interpreted as F4 (floodplain), V3 (valley) as riverine, P4 (piedmont) as alpine, and R5 (riverine) as terrace wetlands. Except the last misinterpretation, no confusion took place between spatially disconnected wetlands. Thus, these confusions stem likely from the inconspicuous boundaries between adjoining wetlands.

Temporal Change in Wetland Area

During 1990–2001, wetlands decreased by 1480.84 km^2 (Table 1) or 17.3 % (Table 2), which is consistent with the trend reported by Cai and Guo (2007) for Maqu located 370 km east of Maduo. All six types of wetland suffered shrinkage with the largest loss observed for alpine wetland at 661.03 km^2 . The next highest reduction was recorded for piedmont wetlands (419.05 km^2), followed by floodplain wetlands (205.02 km^2). In comparison, there is minimal decrease for riverine, valley and lacustrine wetlands. Thus, the order of decrease can be expressed as alpine > piedmont > floodplain > lacustrine > valley > riverine. In general, the amount of wetland shrinkage is positively correlated with wetland altitude ($R^2 = 0.718$) because there is less hydrologic replenishment at a higher elevation (Fig. 3). The relationship is nearly perfect

Fig. 1 Geographic location of the study area, Maduo County in southern Qinghai Province of western China

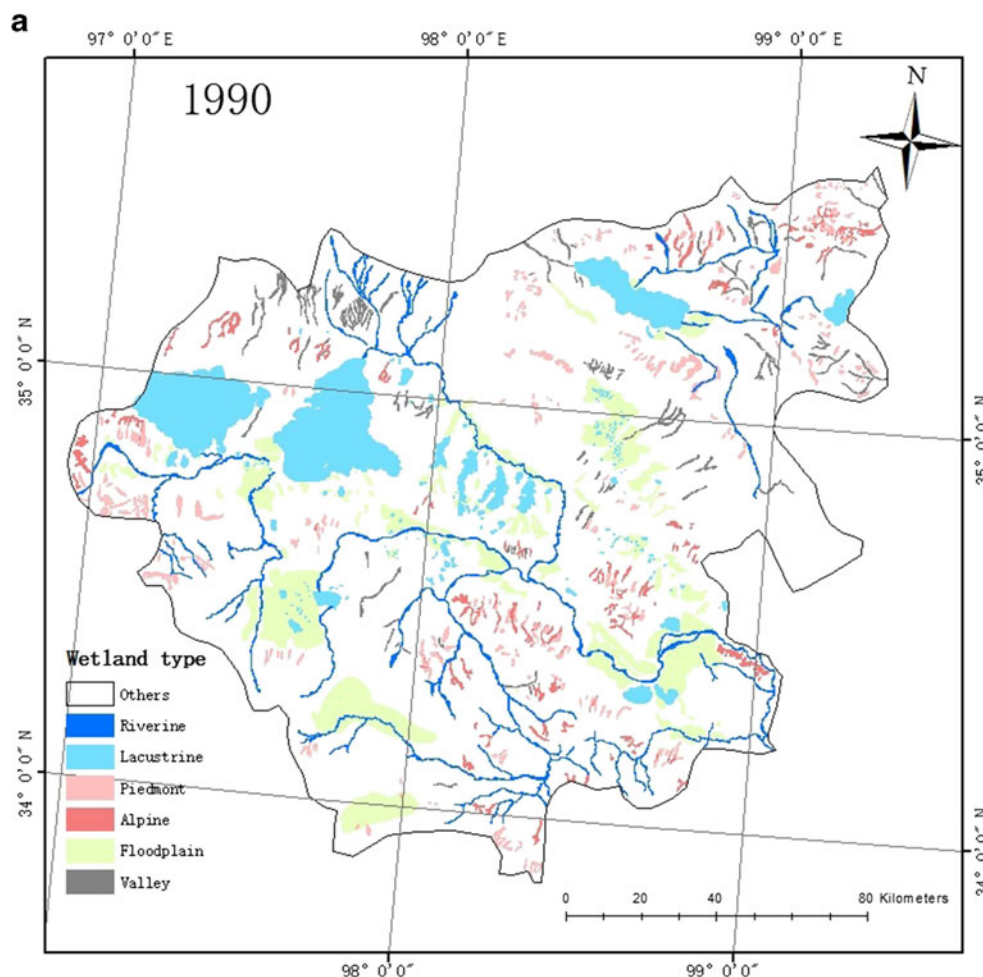


Fig. 2 Spatial distribution of wetlands by type for the different years. Top-1990; middle- 2001; and bottom-2013

for all wetlands except valley and riverine because they are charged more generously by water from all the surrounding environs, and hence the least susceptible to shrinkage.

Relatively speaking, piedmont wetland has the highest rate of decrease (28.7 %), slightly higher than 23.6 % for alpine wetland (Table 2). All other wetlands have a rate of decrease lower than the average rate of 17.3 %. Of the six types, valley wetland is the most stable, losing only 5.1 % during the decade, followed by lacustrine wetland (7.4 %). In terms of velocity of change, alpine wetland disappeared at the quickest pace of $60.1 \text{ km}^2 \cdot \text{yr}^{-1}$, followed by piedmont at 38.1 km^2 per annum. Floodplain wetland shrank at a pace much below this, but much higher than valley and riverine wetlands.

The trend of change in wetlands during 1990–2001 was reversed over the following decade with a gain of 910.95 km^2 (Table 1). All six types of wetlands expanded in size during this period. Alpine wetland gained the most at 309.39 km^2 , followed by piedmont wetland (198.9 km^2). Both valley and floodplain wetlands expanded by nearly the same amount around 114 km^2 . The order of gain follows the sequence of alpine > piedmont > lacustrine > floodplain >

valley > riverine, which is nearly identical to the order of loss during the preceding decade except the position of lacustrine wetlands (Table 1). Thus, those wetlands that lost the most over the preceding decade also gained the most over the following decade except lacustrine wetlands. The order of gain is identical to the order of velocity of change. Dissimilar to the previous decade, the velocity of change has a much narrower range from 1.2 (riverine) to 25.8 (alpine) $\text{km}^2 \cdot \text{yr}^{-1}$ (Table 2). In terms of the rate of change, the order is piedmont > valley > alpine > lacustrine > floodplain > riverine, which bears no relationship with the order of absolute change. This order is quite different from that over the previous period.

Overall, during 1990–2013, the wetlands in Maduo experienced a net loss of 569.89 km^2 (Table 1). All six types of wetlands suffered a loss except lacustrine and valley wetlands. Alpine wetland lost the most at 351.64 km^2 , followed by piedmont wetland (220.15 km^2). Floodplain and riverine wetlands suffered a loss totaling around 100 km^2 . In contrast, lacustrine and valley wetlands gained slightly. Alpine wetland, piedmont wetland and floodplain wetland had one of the highest velocities of change and rates of change (Table 2). These changes

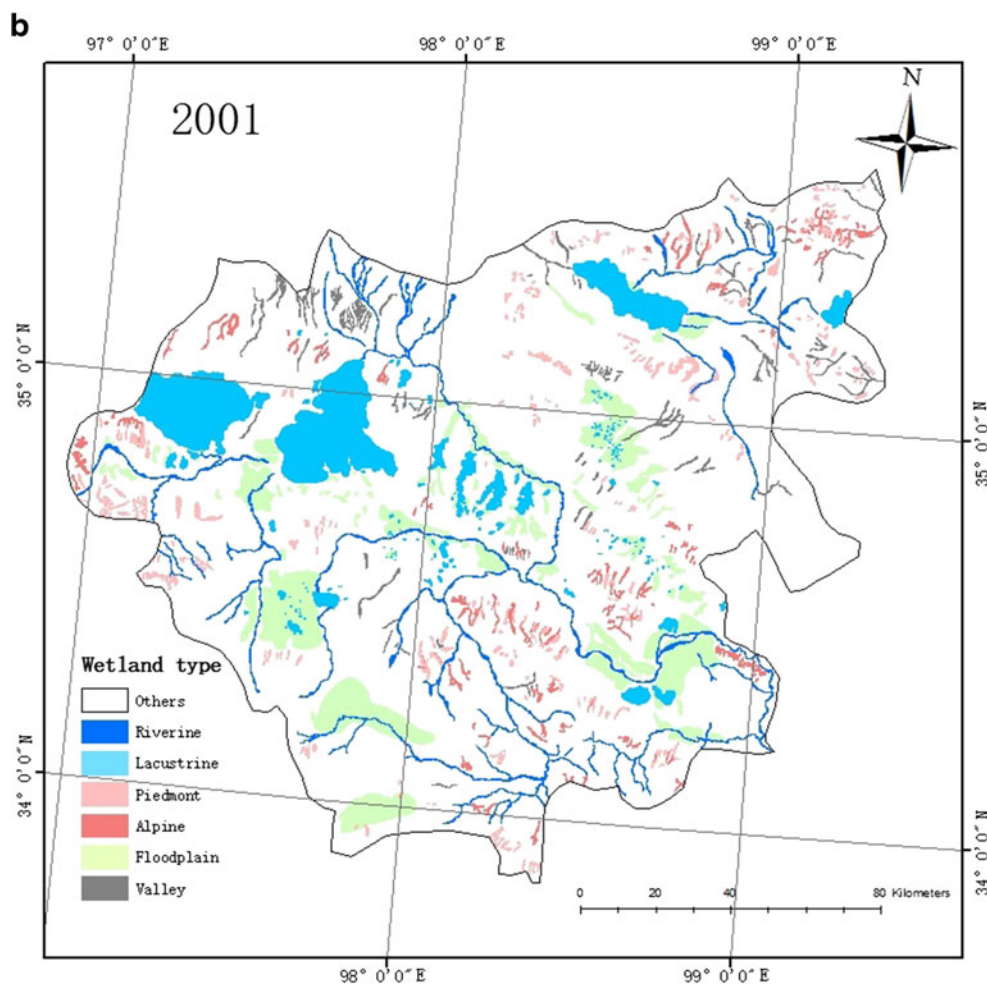


Fig. 2 (continued)

demonstrate that high-elevation wetlands tend to lose while low-lying wetlands experience a gain.

Dynamic Changes Among Wetland Types

Because of a wetland's unique morphologic association, it is not common for one type of wetland to be converted to another on a grand scale no matter how hydrology has changed over a period (except slight shift in demarcating its boundary during visual interpretation). However, it is possible for one wetland to be converted to non-wetland during persistent droughts or vice versa. Besides, some wetlands at the same or a similar elevation are interchangeable as a result of changed water level (e.g., from riverine to floodplain). Shown in Table 3 are major changes among wetlands, and between wetlands and non-wetlands (due to the small physical size of some wetlands, it is impossible to show the spatial distribution of such changes in Fig. 2 legibly).

During 1990–2001 all wetlands lost some to non-wetlands (Table 3). Recharged from both sides by tall mountains, valley wetlands lost the least even in light of droughts. Of the

remaining five types, alpine wetland had 21.87 % converted to non-wetlands, followed by piedmont wetland (25.56 %). Floodplain wetland had 17.12 % converted to non-wetlands. The percentage of loss for other wetlands is lower than 10 (e.g., 9.47 % for riverine wetland, 8.35 % for floodplain wetlands, and 3.35 % for lake wetlands). Shown in Table 3 are the reasonable changes defined as the change between spatially adjoining wetlands. Unreasonable changes between spatially disjointed wetlands such as from alpine to riverine wetland amount to 0.045 %, confirming that the interpreted results are consistent and accurate. From 2001 to 2013, the amount of wetland converted to non-wetlands was drastically reduced, with no change exceeding 87.5 %. Most of the changes among different types of wetlands are small in percentage and reasonable, with the largest being from riverine to floodplain at 6.35 %, followed by the change from floodplain to riverine and from riverine to lacustrine (5.35 %). Such dynamic changes are expected in light of increased rainfall (see section 4.4 below). The low rate of irrational conversion between wetlands confirms once again that the interpreted results are highly reliable and credible.

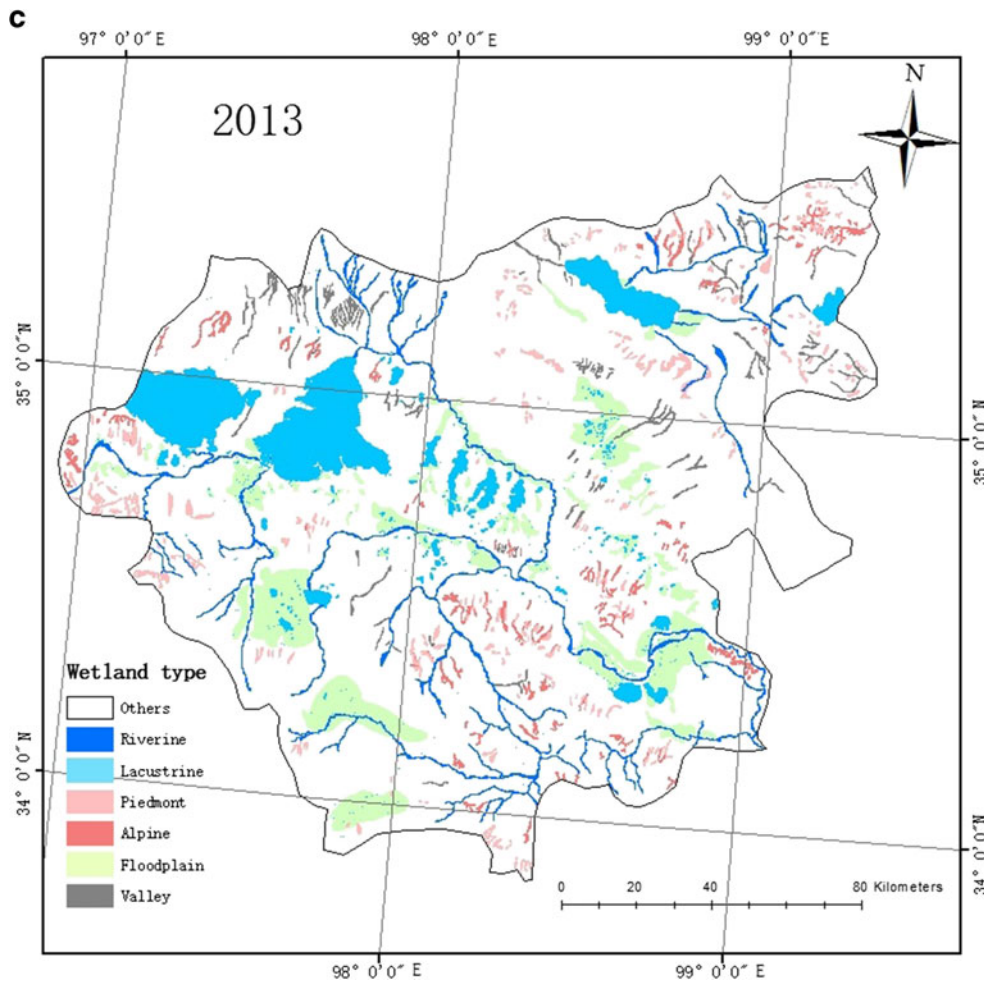


Fig. 2 (continued)

Impact of Natural Variables on Wetland Change

Mean annual temperature in Maduo fluctuated between -4.5 and -2.5 °C during 1990–2001 with an indistinctive trend

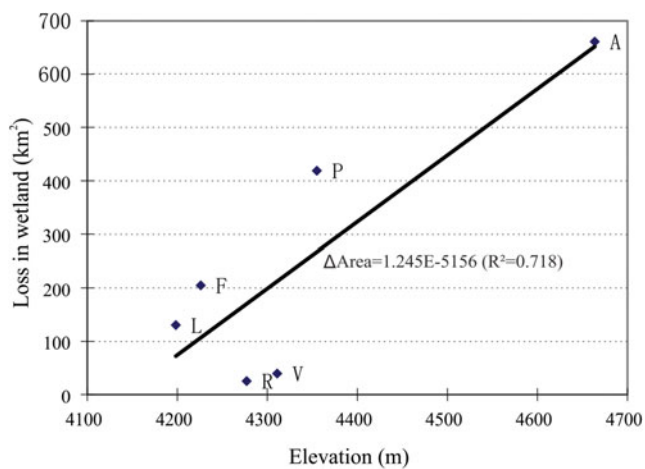


Fig. 3 Relationship between loss in wetland area and elevation (E) (V – valley; F – floodplain; L – lacustrine; P – piedmont; A – alpine)

(Fig. 4). From 2001 and 2013, yearly temperature fluctuated between -3.5 to -2 °C. Apparently, the climate has warmed by 1.2 °C over the preceding decade. Compared to the annual temperature, the warm season (June–August) temperature is more critical to change in wetland areas that are mapped from the warm season satellite imagery. This temperature is more relevant as in this season snow melting is active. As shown in Fig. 4, there is a steady increase in warm season temperature during the study period. It fluctuated periodically and steadily with a rise of 0.5 °C during 1990–2001 according to the established regression model, but stayed stable with a rise of 0.65 °C over 2001–2013. In spite of the warmer temperature, no wetlands shrank during 2001–2013. Thus, climate warming has a minimal effect on wetland areas during the study period, especially over 1990–2001. The explanation is that a warmer climate is conducive to more snow melting, thus those at a higher elevation can actually benefit from it. More alpine ground is recharged by the melting snow. Besides, deeper permafrost thawed under a warm temperature regime is also conducive to healthy wetlands, even though more moisture may be lost from wetlands at a lower elevation due to enhanced evaporation.

Table 3 Conversion among wetlands and between wetlands and non-wetlands (%)

| Period | 1990–2001 | | | 2001–2013 | | | |
|------------|-----------|-----------------|-------------------|-----------|-----------------|-------------------|-------------------|
| | No change | To non-wetlands | To other wetlands | No change | To non-wetlands | To other wetlands | From non-wetlands |
| Riverine | 75.5 | 9.47 | 8.35F, 2.1 V | 87.5 | 1.47 | 6.35F, 5.35 L | 3.45 |
| Lacustrine | 86.45 | 5.3 | 4.56F | 93.45 | 1.3 | 5.56F | 2.03 |
| Floodplain | 73.65 | 17.12 | 6.67 L | 89.65 | 0.92 | 5.35R, 3.67R | 3.05 |
| Alpine | 73.54 | 21.87 | 2.23P | 93.54 | 2.17 | 1.56 L, 1.56 V | 2.78 |
| Piedmont | 70.45 | 25.56 | 1.58 A | 91.45 | 1.56 | 1.89 A, 1.78R | 6.23 |
| Valley | 93.54 | 0.05 | 2.35F | 96.54 | 0.156 | 1.04 L | 7.01 |

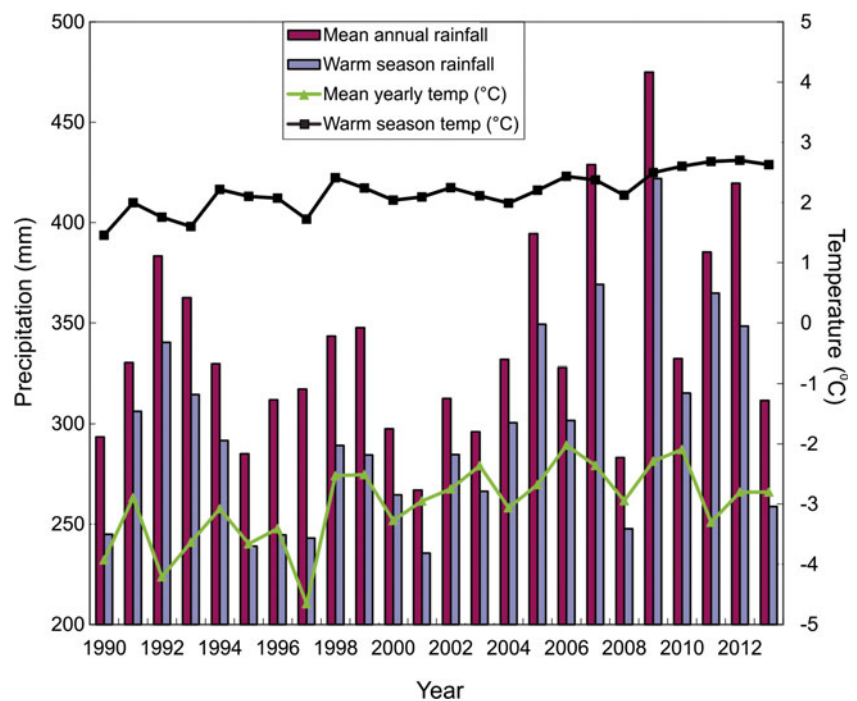
Letter: type of wetlands, V valley, F floodplain, L lacustrine, P piedmont, A alpine

Both annual precipitation and warm season rainfall peaked around 1992 and 1998 over the first decade (Fig. 4). Afterwards, they started to decrease until 2001 when they reached their lowest values. In general, precipitation became noticeably more abundant during 2001–2013 with a definite but fluctuating trend of increase. Cumulatively, annual rainfall summed to 3868.9 mm during 1990–2001, and to 4565.6 mm during 2001–2013, representing an increase of 18 %. The increase of 23.23 % is even higher for warm season rainfall. More rainfall means more hydrological recharge to the wetlands. On average, 87 % of annual rainfall occurs in the warm season. Therefore, the increased precipitation during 2001–2013 is the major cause behind the observed expansion in wetland area. This assertion is supported by the change in alpine and piedmont wetlands. Having the highest elevation among all wetlands, their major sources of hydrologic replenishment is rainfall and snow-melting. While snow-melting

caused by a higher temperature regime is more conducive to healthy wetlands, it is rainfall that is more important in preventing wetland area from shrinking. Similarly, the expansion of lacustrine wetland during 2001–2013 can also be attributed to the more abundant water, and hence a higher water level during this period.

The detected expansion in wetland area during 2001–2013 (Table 2) is consistent with that reported by NDRC (2014). Owing to the implementation of the Qinghai Ecological Protection and Construction Project in Sanjiangyuan (three river source zone) (phase I) with an investment of 7.5 billion RMB (about US\$1.2 billion) from 2004 to 2012, the area of wetlands expanded while conservation of water and soil resources has been clearly strengthened (NDRC, 2014). The significant increase of warm season rainfall during 2001–2013 is attributed to the Artificial Precipitation Enhancement Project at a cost of 1.9 billion

Fig. 4 Mean annual temperature, warm season temperature, annual precipitation and warm season rainfall of Maduo from 1990 to 2013 (source: Qinghai Meteorological Bureau)



RMB. Commensurate approaches to the management of water resources in the headwater zone of the Yellow River have facilitated a stable and sustainable ecological prospect (Li et al. 2012).

Impact of Human Variables on Wetland Change

In the literature, human economic activities are identified as responsible for the destruction of physical and chemical properties of both vegetation and soil that have contributed to a decreased vegetative cover in wetlands (Xu and Liu 2007; Xu et al. 2008). Compared with natural factors, human influence on wetlands is more immediate, and its damage longer lasting. Two types of human factors are discussed here, human population and livestock size.

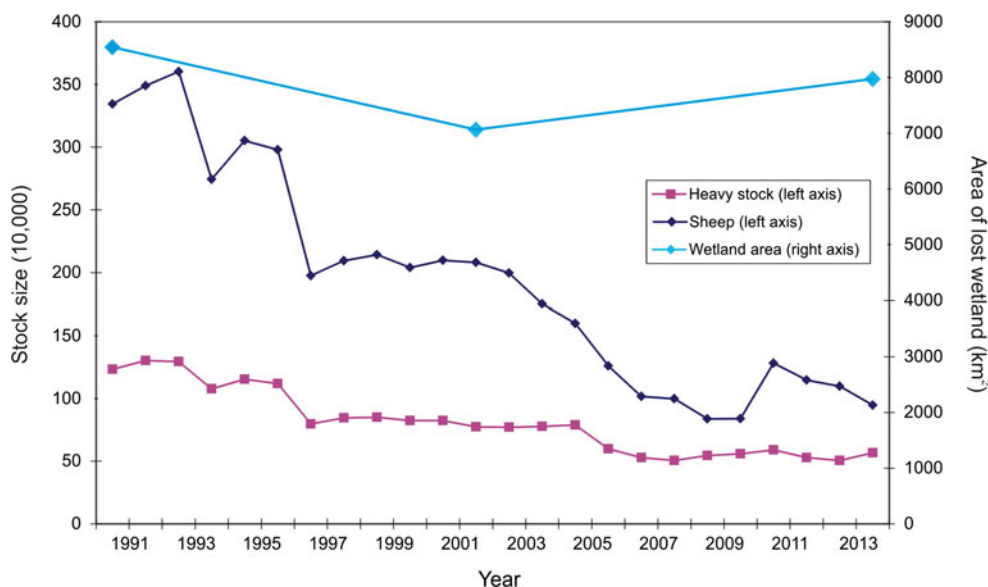
Human Population Human population in Maduo County rose from 9847 in 1990 to 10,799 in 2000, an increase of 952 persons or by 9.7 %. From 2001 to 2013 human population increased further to 14,570 or by 3771 (34.9 %), much higher than 9.7 % over the preceding decade. However, it is during the recent decade that wetlands expanded in their area. Therefore, human population does not seem to have contributed to the observed increase in wetland area. However, two aspects need to be considered: 1) that people have switched their occupations from livestock grazing to other alternatives, making these wetland areas subject to less disturbance; and 2) that there is an increased consciousness in protecting these areas, although this would require more in-depth study exceeding the scope of this paper.

Livestock Size With animal husbandry as the chief economic activity in Maduo, it is expected that livestock population

grew under a burgeoning population since the 1960’s. Overgrazing reduces biomass of swampy meadows, and accelerates loss of moisture from wetlands. Realizing this negative impact, the government has persuaded the local herders to reduce their livestock size (Fig. 5). The population of heavy livestock (including yaks and horses) and sheep dropped by 54 % and 71.7 %, respectively, during the study period. The decrease was 37.4 % and 37.7 % for heavy livestock and sheep, respectively during the first decade, and 26.7 % and 54.5 % for heavy livestock and sheep, respectively, during the second decade. Therefore, the faster reeducation in livestock size during 2001–2013 has helped wetlands to regain some of the loss suffered during the preceding decade. One possible explanation for the shrunk wetland area during 1991–2000 is that the absolute livestock population still stayed at a level detrimentally high to the environment despite the reduction in its size.

This reduction in livestock size is attributed to the implementation of the “Overall Plan for the Ecological Protection and Reconstruction of the Natural Reserve in Sanjiangyuan of Qinghai” since 2000. With this project, pastoralists emigrated ecologically out of grazing in some pastures of low and extremely low vegetative cover. Grazing was prohibited in some grassland. The immediate effect of such efforts can be seen from satellite imagery. Aboveground biomass in 2009 was markedly higher than in 2008 (Zhao et al. 2012). In both years the theoretical carrying capacity of the grassland exceeded the actual ones. Indeed, the tipped balance between grazing and livestock size has been gradually rectified, and the grassland resources have been on recovery. With better vegetative cover, more water and moisture are preserved locally and more moisture is evaporated. This has initiated a benign cycle with increased rainfall over the last decade.

Fig. 5 Variation in stock size of heavy animals (including yaks and horses) and sheep in relation to wetland change during 1990–2013 (data source: Qinghai Provincial Statistics Bureau)



Conclusions

There were 8542 km² of wetlands in 1990 in Maduo County, accounting for nearly one third of its territory. They are dominated by alpine wetland (32.8 %), lacustrine wetland (20.5 %), floodplain wetland (18.1 %), and piedmont wetland (17.1 %). From 1990 to 2001, wetlands decreased by 2799 km² in area, with all six types of wetland reducing their extent. The quantity of wetland loss is positively correlated with the elevation of wetlands ($R^2 = 0.718$). Namely, those located at a higher elevation suffered more loss. Alpine wetland lost the most at 28.7 %, followed by piedmont wetland at 23.6 %. During 2001–2013, wetlands expanded by 910.95 km² in area, with all types of wetland expanded in their area. Those located at a higher ground gained more than those at a lower elevation. This order of gain follows closely the order of loss over the preceding decade. Although this finding is obtained from one study area in the headwater zone of the Yellow River, it should be applicable globally. Apart from lacustrine and valley wetlands that gained a total of about 100 km² during 1990–2013, all others experienced a net loss in their area. The major types of change are characterized by conversion from wetlands to non-wetlands during 1990–2001, and from non-wetlands to wetlands during 2001–2013. Changes among different types of wetlands are minor in magnitude.

Both annual temperature and warm season temperature were higher during 2001–2013 than over the preceding decade. However, such a rise did not translate into wetland loss. In contrast, cumulative annual rainfall increased by 18 % from 1990 to 2001 to 2001–2013. The increase is even higher (23.23 %) for warm season precipitation. It is concluded that more abundant rainfall during the 21st century, which resulted mostly from the Artificial Precipitation Enhancement Project, is the main reason for the increase in wetlands. Compared with rainfall, temperature has played a minor role in the observed wetland change. The increased rain in Maduo during 2001–2013 can be partially attributed to the implementation of the Sanjiangyuan ecological protection project with which livestock size, especially sheep, was reduced by 71.7 % during the study period (54.5 % during the 21st century). The change in wetland area is not related to human population. More research is needed to ascertain the relative importance of increased rainfall and reduced livestock size to the observed wetland change. Since climate cannot be changed easily, the best way to accomplish this is to minimize human impact on the environment. With the factors that affect these wetland changes, future work may also include longer time series of Landsat or future available space-borne sensors to establish a more robust link between long-term effects regarding the human activities and possible climate change.

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